Department of Physics

PROJECT ASSESSMENT SHEET – (Supervisors)

Years 3/4 2012/2013 **PHYS379/PHYS386/PHYS396/PHYS360/PHYS 395/PHYS 398/PHYS498**

Supervisors are asked to use this sheet to record their assessment of a project.
Return assessment sheets plus Projects to the Student Office by 31st May 2013 at the latest.
Your comments are returned to the students on the separate sheet as part of the feedback criteria.
Maximum marks have been allocated to each element and you are required to assess your student's achievements and note the marks obtained for each section. The overall marks should reflect the standard mark bands for degree classes. Please refer to the attached marking descriptors when deciding a mark and ensure that both the partial and the overall marks agree with the marking descriptors. Second markers will assess on the basis of criteria 1 to 6 on the same mark scale to allow a direct comparison of the two marks.

Student Name: Dillon, Jeremiah

Supervisor Name: Kai Hock

	Heading	Maximum Mark	Mark Obtained
1	Contribution to achieving the project aims	10	
2	Ability to apply physics to progress the project	10	
3	Appreciation of the methodology used. May include pilot projects, test phases or justification of a chosen design/way of accessing the task	10	
4	Evaluation of the results and / or outcomes. e.g Evaluation of statistical & systematic uncertainties, consistency of presented results, completeness of analysis	10	
5	Organisation of the report. e.g Use of numbered chapters (abstract, Intro etc) references and their correct use, figure & table captions and their correct use	10	
6	Quality of presentation of the report. e.g general layout & style, consistency of used colour code & style of plots, quality of language (diction, grammar, spelling) completeness of raw data (can also be in the appendix) referencing of claims	10	
	Sub –total	60	
7	Student initiative (in practical work or analysis)	20	
8	Use of time / diary (student organisation)	10	
9	Diligence of student (timekeeping, effort)	10	
	Total	100	

Simple Marking Descriptor				
10 = Masterpiece	9 = Excellent	8 = Very Good	7 = Good	6 = Quite Good
5 = Reasonable	4 = Just Adequate	3 = Poor	2 = Very Poor	1 = Disaster

Note: Categories 2, 3 and 4 in the above table should be interpreted broadly to cover those projects which do not have a number to calculate. Some examples are given below:

2 Optimising use of the instrumentation, e.g in a Microlink based project.
3 Appreciation of the context of the experimental measurements in a detector development project.
Appreciation of how the instrumentation achieves the required outcome in a Microlink project
Note: For some projects, categories 2 and 3 may overlap. E.g. Understanding of the algorithm used in the code in a computer based project, please consider then an overall average mark for those categories
4 How well (or otherwise) a piece of equipment or computer programme worked, measured against the aims

Comments on Project overleaf - *(these comments are returned to the student)*

Student Name: ......Dillon, Jeremiah......

Supervisor Name: ......Kai Hock......

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THE UNIVERSITY OF LIVERPOOL

The Industrial Application of Electron Beams

With Specific Focus on 3D Printing

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May 2013

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Acknowledgements: James Hunt

Abstract: This report contains a survey and analysis of the literature currently available concerning the research and development of electron beam use in general, and in 3D printing in particular. A brief overview of electron beam technology has been included for reference, as has an overview of the industrial application of electron beams in areas other than 3D printing. 3D printing, also known as Additive Layer Manufacture (ALM), is defined and two current methods of electron beam ALM are described - *Beam Deposition* and *Electron Beam Melting (EBM)*. The advantages/disadvantages of current techniques are assessed. An insight into new ALM technologies is also given. Through summary of this information potential future directions for Research and Development of 3D printers are proposed.

Contents

1. Introduction

The use of the electron beam has evolved. Originally a source of fascination to the scientists of the 19th century, it is now of valuable importance to both consumers and producers alike.

Low energy electron beams were vital to the development of the original television set and are found it almost all sets produced before 1995. Indeed, Albert Abramson writes in the history of television, 1880 to 1941: "The disclosure of the Kinescope [described later] changed the history of television. Zworykin's tube was the most important single technical advancement ever made in the history of television." (1)

Electron beams have revolutionised many industrial processes. Clean electron beam Sterilisation of food stocks, water supplies and equipment is far superior to traditional methods involving thermal or chemical techniques. Electron beam crosslinking of polymers helps to create new materials with high functional performance, such as thin film shrink wrap, and performance plastics exhibiting high thermal resistance. Electron beams can also be used to accelerate the breakdown of waste polymers, creating none of the toxic fumes associated with traditional pyrolysis (thermochemical decomposition).

Potentially the biggest area for development is electron beam technology in 3D printing, or to use its formal term Additive Layer Manufacturing (ALM). ALM describes the process of building a 3D object out of material layer-by-layer. The term encompasses a huge variety of different manufacturing methodologies, many not involving electron beams at all. However, all share the common goal of improving functional performance of the final product and reducing waste (be it production cost or material waste). Since, the focus of this report is the application of electron beams in ALM, many of the other methods are not mentioned, although a few are touched on.

2. Electron Beam Physics

An electron beam is created by applying an electric voltage across a conducting cathode. Resistance in the cathode causes it to heat up. As it heats up, it liberates electrons through thermionic emission. The electrons are then accelerated towards a positively charged anode, gaining energy equal to the potential difference between the cathode-anode. This beam can exit via an aperture in the anode and be directed at a target. The whole process must be carried out in a vacuum; otherwise the electron beam would lose too much energy through collision with air molecules.

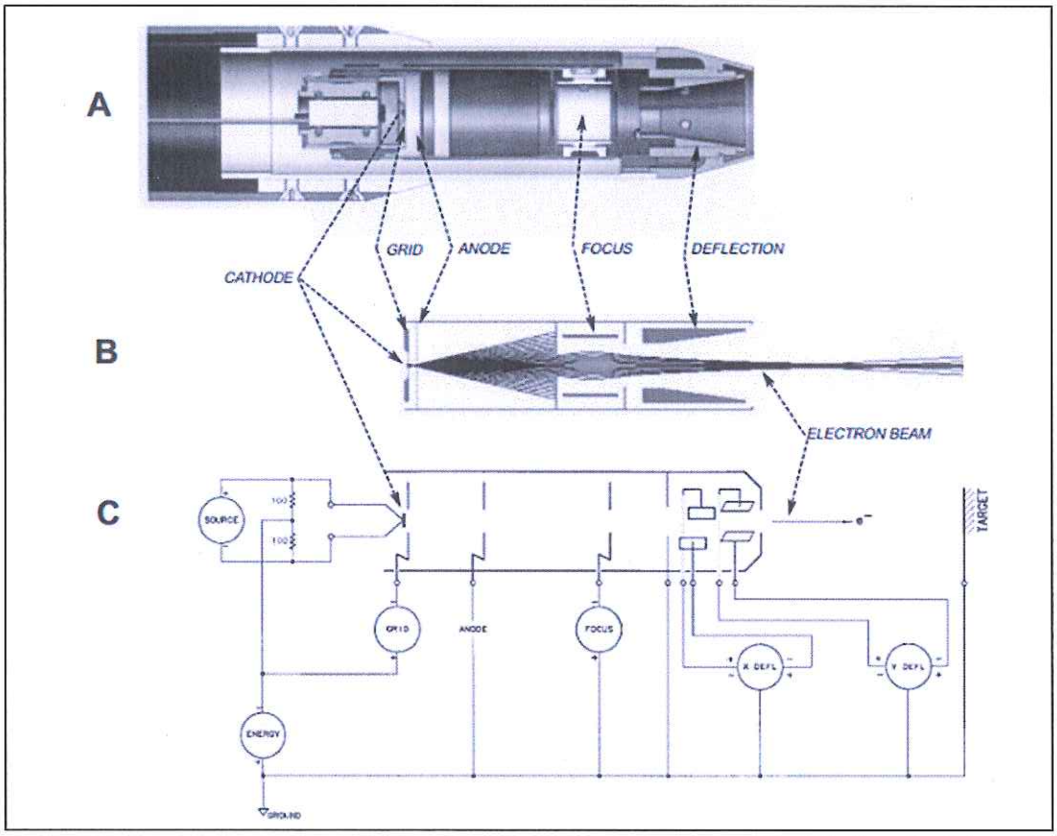


Figure [2.1] Electron Gun Schematic

2.1 Electron Gun

The gun is the collective term given to all of the parts involved in the production of the electron beam. The electron gun is a descendant of the early cathode ray tube and some parts still bear the old fashioned names, although now different in structure.

Electron Beams can be produced of varying energies:

- Low Energy Electron Beams: 5eV – 1000eV
- High Energy Electron Beams: 100+keV (2)

Electron gun size tends to increase with the energy of the produced beam. Electron guns can range from a few centimetres in length (ex. Low Energy Electron Diffraction), right up to a couple of meters (ex. Electron Beam Welding).

An electric current is used to heat up the cathode. The cathode might simply be a conducting wire, which emitts electrons directly from it's surface. Indirect production is more common in high power electron beams however, utilising a disk emitting surface. A resistive wire, termed a heater, is wrapped around a disk of appropriate emitting material. When a current is applied to this wire heater it warms due to resistance, causing the disk to heat up and emit electrons.

The minimum amount of energy needed for an electron to break free from the surface of a metal is known as the work function of the metal. The typical metal of choice for directly heated cathode's is Tungsten which has a work function of $\sim 4.5eV$. For the production of electron beams used in 3D printing the cathode is typically heated to $> 2500K$

The lower the work function, the lower the required heater current. Thus it is desirable to use a material with a low work function as a cathode. The oxide layers that form on the surface of certain elements (ex. Barium & Calcium) dramatically reduce their work function. The electrons in these sources are emitted through a process called Schottky Emission, and they are termed field-emission sources. They give monochromatic electrons (i.e. all carrying the same energy). However, low work function materials are not used in the production of high energy electron beams as they break down at high voltages.

The electrons are accelerated towards a grounded anode. The energy (in electron volts) gained by the electrons is equal to the potential difference between the cathode-anode plates. The total current generated by electrons passing through the potential difference is termed the emission current. However,not all the electrons emitted from the cathode leave the gun. Some land on other elements of the gun column, and thus the final beam current is often less than the emission current of the gun.

2.2 Electro-static Lens

An electrostatic lens is used to focus the electron beam in the same way that an optical lens acts on visable light. Typically, electrostatic lenses consist of a number of cylindrical elements, and the electron beam passes through the center. By varying the potential across the cylinders, and so the constant electric field within their centers, the electron beam can be focused.

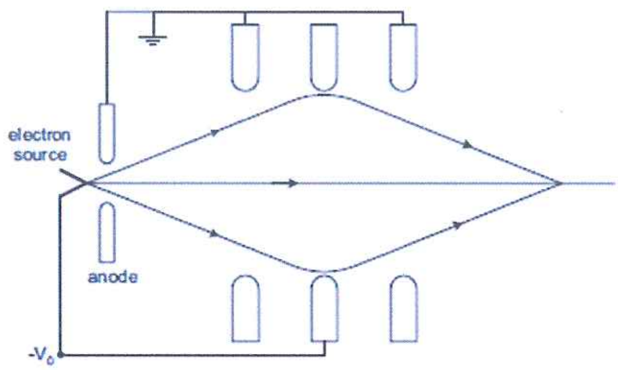


Figure [2.2] Representation of an Einzel. The electrodes, seen here in cross section, are circular disks containing apertures.

Note that the electrodes, and therefore the electric fields which give rise to the focusing, have cylindrical or axial symmetry, which ensures that the focusing force depends only on radial distance of an electron from the axis and is independent of its azimuthal direction around the axis and its position along the axis. To a first approximation, the deflection angle is proportional to displacement from the optic axis and a point source of electrons is focused to a single image point. (3)

Most electrostatic lenses consist of three elements which together form a converging lens called and Einzel. These can be seen in the figure 2 above. The potential across the elements is determined by their own independent power supply. Depending on the arrangement of the anode and electro-static lenses, wide beams (flood beams) or narrow beams can be produced.

2.3 Detector

For the purpose of many applications (ex. scattering experiments, oscilloscope trace) an electron detector is required. For the purpose of 3D printing this is not the case. However the details will be documented for generality. There are two common types of detector:

i.) **Phosphor Screen** – Emits photons when bombarded by high energy particles. On the screen, a focused beam of electrons will appear as a sharp spot. An unfocused beam will appear larger, with fuzzy edges, or be made up of many dots (beamlets). The phosphor screen is useful in analysing beam alignment.

ii.) **Faraday Cup** – Measures the actual beam current emitted by the gun. The working principles are very simple. It consists of a shielded cup with an aperture, which collects electrons and an output wire connected to an ammeter. An array of small Faraday cups, or alternatively, a Faraday cup mounted on a linear manipulator, can be used to measure the distribution of beam current across the spot. This is useful for analysing beam uniformity.

2.4 Beam Parameters

- **Brightness** – This is the current density per unit solid angle of the source and it increases linearly with increasing accelerating voltage.
  The brightness is essentially the number of electrons bombarding the target area each second. Therefore, the greater the brightness the quicker the target is heated/irradiated through transfer of the kinetic energy of electrons in the beam to the nuclei/electrons of atoms in the target.

- **Beam Noise** – Indicates how the current density of the beam varies with time. It is inversely proportional to the emission area and so smaller sources are more susceptable to noise. Beam noise must be reduced in applications such as microscopy as it will present itself in the form of backround noise in the computer generated image.

- **Coherency** – A measure of the relative phase differences between the emitted electrons. Field emission sources mentioned earlier have a very high beam coherency, analogous to a monochromatic light source.

- **Spot Size** - The electron-intensity distribution of the electron beam is approximately of Gaussian form, and the beam diameter ($\propto$ spot size) is defined as the full-width at half-maximum (FWHM) of the Gaussian. The spot size can be altered using an electro-static lens, with higher power lenses giving smaller beam diameters.

3. The Use of Electron Beams in Industry

Electron beams are used in a variety of industrial applications, with many benefits. However, the common, and sometimes single, downside associated with all electron beam technology is the high initial start-up costs associated with equipment/fitting. This is due to many of the processes being in a relative state of infancy. As technologies develop and techniques improve, costs are likely to decrease. Current areas where electron beam technology is utilised include:

3.1 Medical Sector

Electron beams are used for the bulk sterilisation of medical devices. The electrons bombard any bacteria present breaking molecular chains in biological molecules such as DNA. Electron beams are more useful than other methods of sterilisation as the process is quick, cost effective, and compatible with most materials and does not require any quarantine following the processing (4). Typically this involves high energy electron beams of around 5-10MeV, but no higher as there is a risk of inducing radioactivity into the equipment being sterilised (5).

3.2 Sterilisation of Food/Water

Electron beams are used to eliminate the presence of live insects from grain, tobacco and other unprocessed bulk crops. This is particularly important as a quarantine measure when importing/exporting products, as it prevents the spread of insects/plant pathogens. Electron beams can also be used to decontaminate waste/drinking water. Chemical sterilisation (ex. Chlorine) is undesirable as it causes damage to water pipes and creates toxic halogenated organic compounds. Electron beam sterilisation is totally clean and carries none of these problems.

Electron beam sterilisation is not only employed for the direct benefit of humans. Environmentally damaging waste from factories that leaks into the water cycle can be removed using electron beams with no hazardous by products.

3.3 Polymer Degradation

The application of an electron beam causes large scale breakup of the polymer chains, into their constituent monomer parts. This is known as chain scission. It can be used as a method of recycling used polymers, for example the breakdown of waste polytetrafluoroethylene (PTFE or 'Teflon') into fine powder for reprocessing (6). The degradation of bio-degradable waste can be accelerated by using electron beams in this method.

This process is environmentally important as, unlike burning, it enables neutralisation of any hazardous waste products as they are produced. Also, because no chemicals are used (as in other methods used to induce scissioning), there are no unwanted residuals in the final product. Toxic residuals left behind often require post-processing. An example of this is the chemical de-halogenation (removal of halogens) of waste. Toxic Halogenated compounds are also produced by traditional pyrolysis (burning) of plastics. In electron beam polymer degradation, these toxic compounds are eliminated.

3.4 Cross Linking

Alternatively, when used in lower doses, electron beams can be used to join together multiple long chain polymer molecules. An electron beam irradiates the polymer sample, creating ionised monomers that form bonds with neighbouring chains. The degree of cross-linking is easily controlled by varying the energy of the applied electron beam.

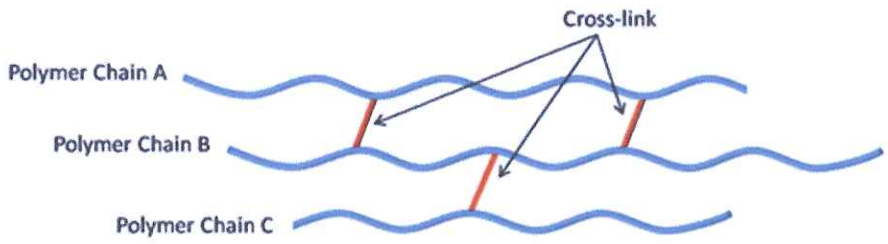


Figure [3.1] Cross linking between multiple polymer chains

The following properties of polymer materials can be improved through cross-linking:

- Mechanical properties, such as tensile strength, elastic modulus, Hardness, etc.
- Thermal properties, including melting point.
- Chemical properties, including reactivity. This is especially important in processing of food packaging
- Permeation reduction. This is a measure of the ease at which gas/liquid can penetrate through the polymer. Again, this is important in the processing of food packaging.
- Heat Shrink – Polymers can be given an elastic memory. This causes an extended polymer to return to its original shape under heating.

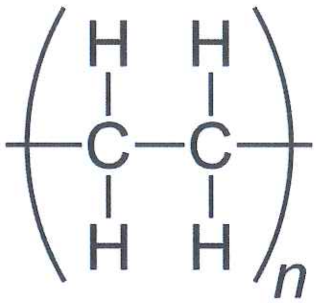


Figure [3.2] Polyethylene Monomer

Electron beams can be used to create new materials with desirable properties. A good example of this is everyday 'shrink wrap'. An electron beam is fired at normal polyethylene plastic. The electrons knock off hydrogen atoms present in the polymer chains. Under the right conditions these vacancies can result in cross-linking carbon-carbon bonds. The polymer starts to knit together. This treated polymer becomes elastic when heated past its melting temperature, but doesn't melt. It can then be stretched into a thin film without tearing. When cooled, it retains its stretched shape. If wrapped around an object (ex. a vegetable) and heated, the plastic shrinks back down to its original size, giving an air tight wrap (5). The property of elastic memory is also exploited in heat shrink tubing used to snuggly insulate electrical wiring.

Cross linking can be achieved through controlled chemical heating (ex. Vulcanisation of rubber by heating with Na) but the use of electron beams enable the process to be carried out much more efficiently, requiring less energy. This however has to be weighed against the high capital cost initially required.

4. The Use of Electron Beams in 3D Printing

3D printing, or to use its correct term Additive Layer Manufacturing (ALM), concerns the process of building a 3D object out of material layer-by-layer. It is the opposite of so called subtractive manufacturing (a retronym), which describes the process of starting out with a large block of material and cutting the desired object from it.

In producing a product through subtractive manufacturing, many 'off-cuts' are discarded. In additive manufacturing, only the material required for the exact shape of the product is processed. Due to the reduced waste, it has the potential to be more economical, and more environmentally friendly than traditional methods.

3-Dimensional digital blueprints can be created from scratch using CAD (computer-aided design) software. Alternatively an existing object can be scanned into a computer. The file can then be sent to the printer (after completion of any required file conversion), in an analogous fashion to printing a simple picture on an inkjet printer.

There are vast arrays of 3D printer processes currently available, and even more prototyped. This project focuses specifically on electron beam utilisation. The most popular electron beam processors currently in use are extrusion based *beam deposition processors* and powder bed *Electron Beam Melting (EBM) processors*.

4.1 Beam Deposition Process

This process is essentially based on electron beam welding (EBW).

In EBW a metallic wire feedstock is fed through a nozzle. The nozzle is positioned over the desired weld, for example between the two sheets to be joined. An electron gun aimed at the wire feed causes it to melt as it is deposited from the feed nozzle. Both the electron gun and the feed nozzle tend to be fixed with the sheets attached to a moving baseplate. The machine is programmed to move the base plate so that the nozzle traverses the weld. As this happens, the wire is fed through and deposited onto the weld site. The whole process is carried out under vacuum.

Beam/Metal Interface

Within the electron beam, electrons are accelerated to a kinetic energy E. When they strike the surface of the metal they can be backscattered or absorbed. The absorbed electrons travel a certain distance, colliding with electrons and ions present in the metal. At each collision, an individual electron will transfer a fraction of its kinetic energy to the ions/electrons of the metal. The depth penetrated by the electrons depends on number of collisions it makes and the energy lost per collision.

In a free atom, the electrons exist in localised shells. Electrons can be excited to higher shells, following absorption of energy. They can then return to their unexcited level by re-radiating the energy as a photon. Alternatively, if the absorbed energy is large enough, the electron can be ejected, leaving the nuclei ionised. An electron bound for an ionised atom can absorbed if it is able to re-radiated any extra kinetic energy it possess.

In the band theory of solids, these discrete shells blend into bands due to the degeneracies of the electrons. Electrons are stacked in energy levels, up to the highest available energy. At low temperature, this is called the Fermi-energy. In non-metals the bands are clearly defined. All energy bands are filled up to the valence band (the highest energy band). In a metallic structure, the gas of free electrons results in an overlap of the band structure. The valence band overlaps with the conduction band, where electrons are free to flow within the solid lattice. This is what gives metals their large conductivity.

The build material targeted by the electron beam must be metallic. Consider an electron beam transferring energy to a material. In a non-metal, the discrete bands result in electrons being absorbed and emitted in very few collisions, and therefore very quickly. Conversely, in a metal, the electrons absorbed from the beam are free to flow and transfer their energy in a large number of lower energy collisions. The free electron gas of metals enables the beams energy to be dissipated much more effectively than in non-metals.

The result is that non-metals tend to build up a net negative charge at the beam-surface interface. This causes a dilution of the beams energy due to coulomb repulsion. The beam width is effectively increased, resulting in a lower power density and less accurate transmission of heat.

The melting point of titanium is around 1600°C so the beam needs to be effective at transferring enough energy to heat to this temperature over a small area of material, but not more, as this will increase the size of the melt pool.

The process of EBW can easily be modified into a form of ALM known as beam deposition. This process can be thought of as layer upon layer of welding, such that a desired shape can be built. The machine is programmed to move the base plate to allow the fixed nozzle to traverse a specified cross section one layer at a time whilst it deposits the wire. As each layer is successfully completed, the base plate is lowered and the next layer is deposited. Time must be given to allow each layer to cool before a new layer is deposited. Layers deposited too slowly can result in a deformed final product, and layers deposited too quickly result in poor joins between layers and uneven mechanical properties throughout the final product.

This process is very primitive. Basic hollow shapes such as cylindrical tubes can be created, but poor control of the melt pool size limits the accuracy and surface finish.*Pictured left is an example of the crude nature of this type of ALM. The layers of 'welding' can clearly be seen. The photo was taken at the Mercury Centre for ALM research, part of the University of Sheffield.

The use of electron beam welders in ALM has now evolved. One method being developed takes a compact powdered core and uses EBW to fuse a surface skin. Powdered metal is loosely compacted into the desired shape using compounds that promote bonding. The EBW is then used to cover the shape with a molten skin, sealing the compact powder centre. The block can then be transferred to a hot iso-static press (HIP), which heats the block under fluid pressure causing further compacting and sintering (expanded on later) of the powdered centre. Alternatively, after the EBW has coated the block with a skin, it can be transferred to a furnace for controlled heating and sintering of the block centre. An inert gas (ex. Nitrogen) is swept through the furnace during the heating in order to remove any gaseous by-products of the melt without oxidising any of the material.

Example: The Helga pro-Beam

At the Mercury Centre I had the opportunity of seeing a Helga pro-Beam electron welder functioning as a 3D printer by means of both the beam deposition process, and the hot iso-static press process.

Overleaf are photos taken of the machine in use.

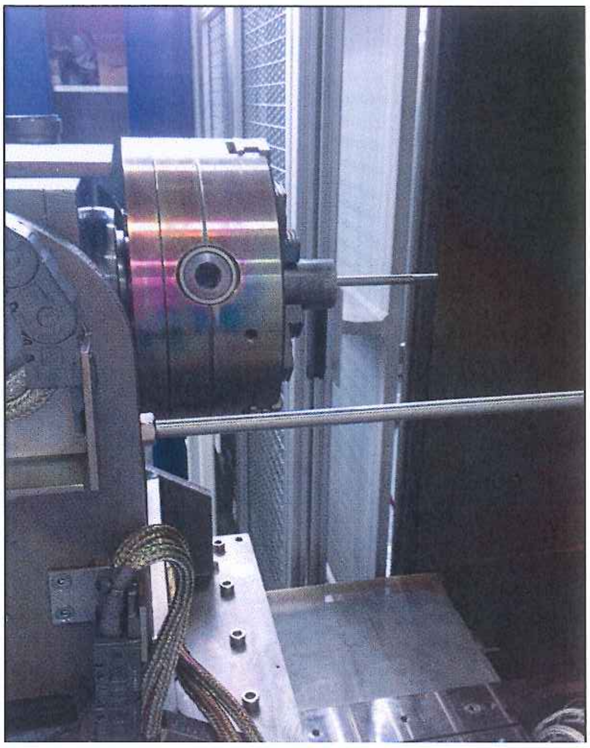
*Please note that all unreferenced photographs within the report were taken by me, whilst at the mercury centre.

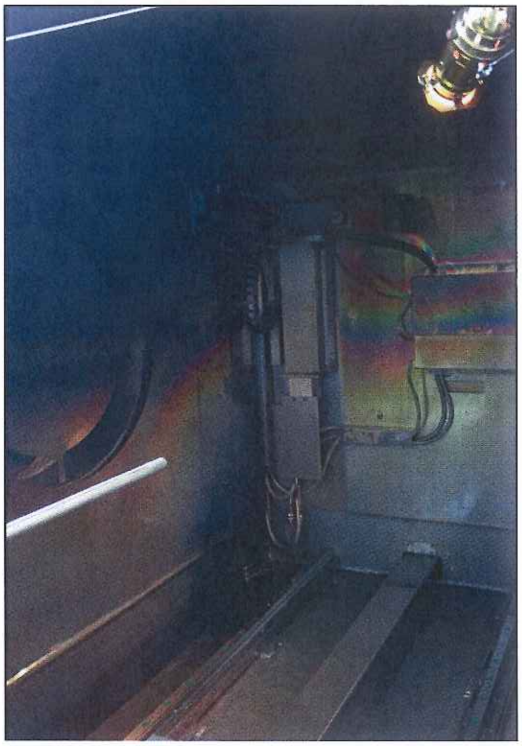
These pictures show the machine as seen from the outside.

Above Left: The large box in the bottom half of the picture is the vacuum chamber. A small window allows the user to look into the chamber, but a protective x-ray shield must be slid across when the beam is on. The electron gun can be seen above the vacuum chamber.

Above Right: This is a more detailed view of the electron gun.

Left: As the door slides across, the vacuum chamber is sealed. It is then ready for pumping. The computer station from which the machine is operated can also be seen.

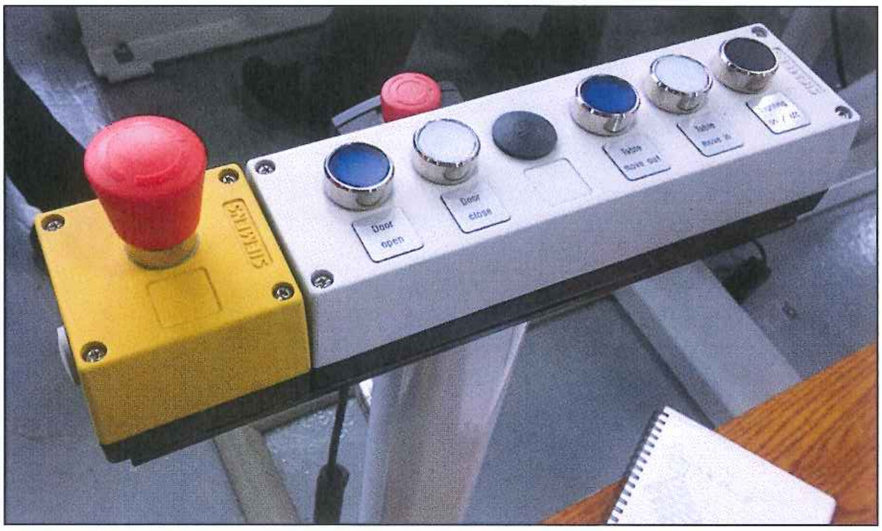


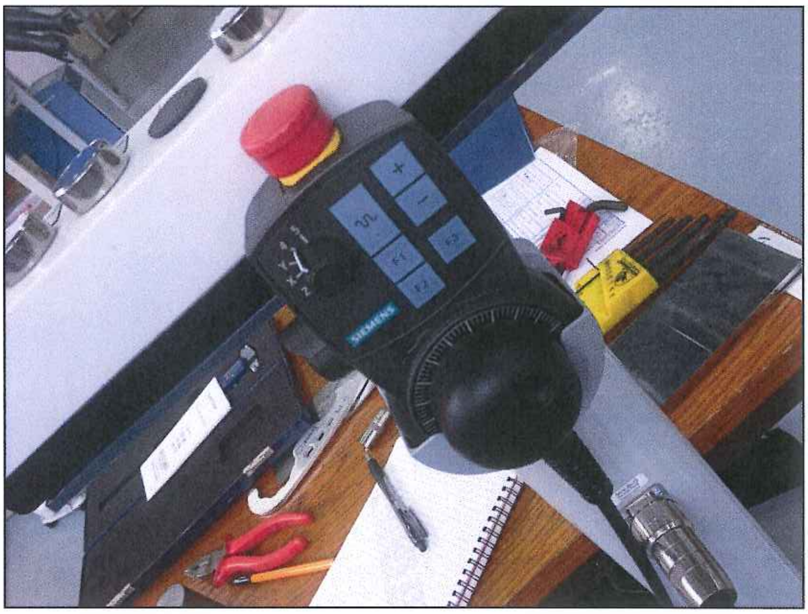


Above Left: In this photograph, a compact powder block core is about to be coated with a molten skin (as described previously). The large cylindrical chuck in the centre of the picture is the base plate. The powder block core (also cylindrical) can be seen secured to the base plate by vices.

Above Right: This is the inside of the vacuum chamber. The base plate moves inside the chamber along runners (bottom of the picture). The baseplate is positioned close to the electron gun/ feed nozzle, and the vacuum chamber is sealed. The electron beam emerges through the hole in the ceiling of the chamber.

Below: The chamber is controlled using the chamber control panel





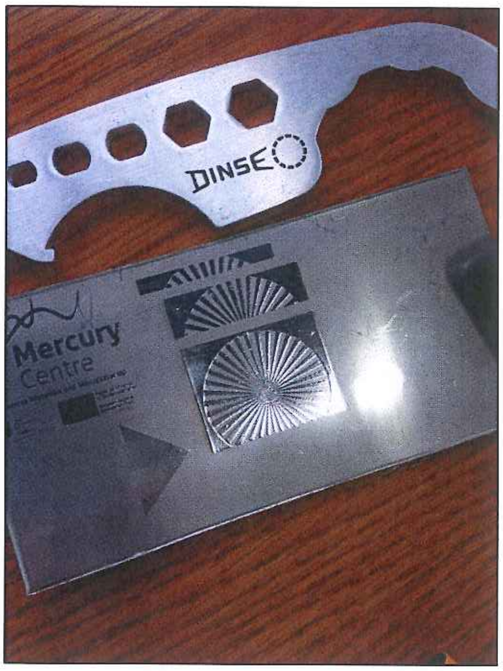
Above: The baseplate and beam is controlled via a purpose built computer station, which operates using simple pre-programmed code to move the base-plate in the x,y,z plane.

Left: The baseplate can be controlled manually using the joystick.

Left: Here, the electron beam has been tested on piece of titanium with the beam parameters being varied.

At slower speeds/greater beam brightness the beam melts deeper into the sheet creating a central valley with mounds either side. Balling can occur if the beam is scanned too quickly - small balls of molten metal are formed due to surface tension forces. This is undesirable in ALM as it reduces the strength of the bonding between different layers.

Right: Electron beam welding gives quite a coarse finish. Conversely, when using very fast scan speeds the beam can etch detailed patterns onto the surface of metals.



Example: The RepRapPro Huxley

Whilst not involving electron beams, it is worth noting that I spent a summer working in a workshop producing RepRapPro Huxley Polymer Printers.

These machines are much simpler on the same principle as the EBW. They differ in that they used polymer build materials and electrically heated gun nozzles. Also, rather than move the baseplate under a fixed nozzle, the baseplate is stationary and the nozzle can move in the x, y, z plane. The absence of the electron beam means they can be operated at atmospheric pressure, and the low melting point of the build material means they do not require any preheating. Due to their ease of use they have become popular amongst hobbyist wishing to get a taste of 3D printing at a very affordable price (ex. RepRapPro Huxley £399).

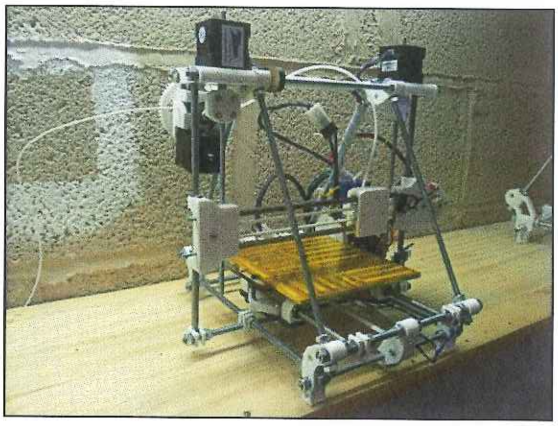


Figure [4.1] A RepRapPro Huxley 3D Printer in use

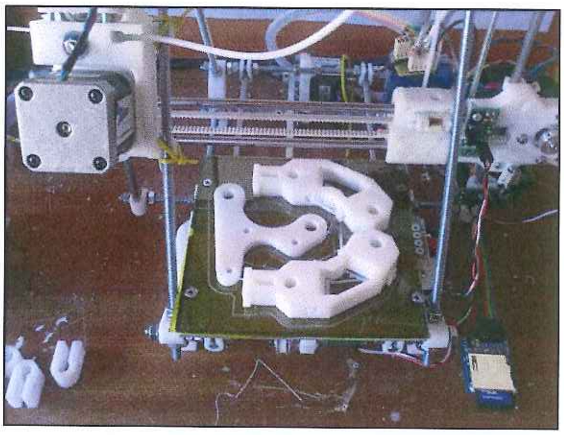


Figure [4.2] The build platform of a RepRapPro Huxley. The white polymer printed product is attached to the build platform

A unique selling point often coined when talking about RepRapPro machines is their ability to print their own replacement parts, and parts that can be used to construct new machines. Hence their name - *replicating rapid prototyper.* This concept could one day be applied to their larger electron beam counterparts.

4.2 Electron Beam Melting (EBM) Process

The EBM processor consists of an electron gun, aimed at a powder bed housed in a build platform. The whole thing is enclosed in a vacuum chamber.

Material is deposited in powdered form, layer by layer on the build platform via a Hopper. The layers are typically between 0.1 – 0.15mm thick. The hopper vibrates at an ultrasonic frequency in order to promote powder flow and even distribution. As the Hopper traverses the powder bed, it is followed by a counter-rotating powder levelling roller which ensures even depth across the layer.

The whole chamber is thermostatically controlled at a temperature just below the melting point of the build material. (7 p. 104).

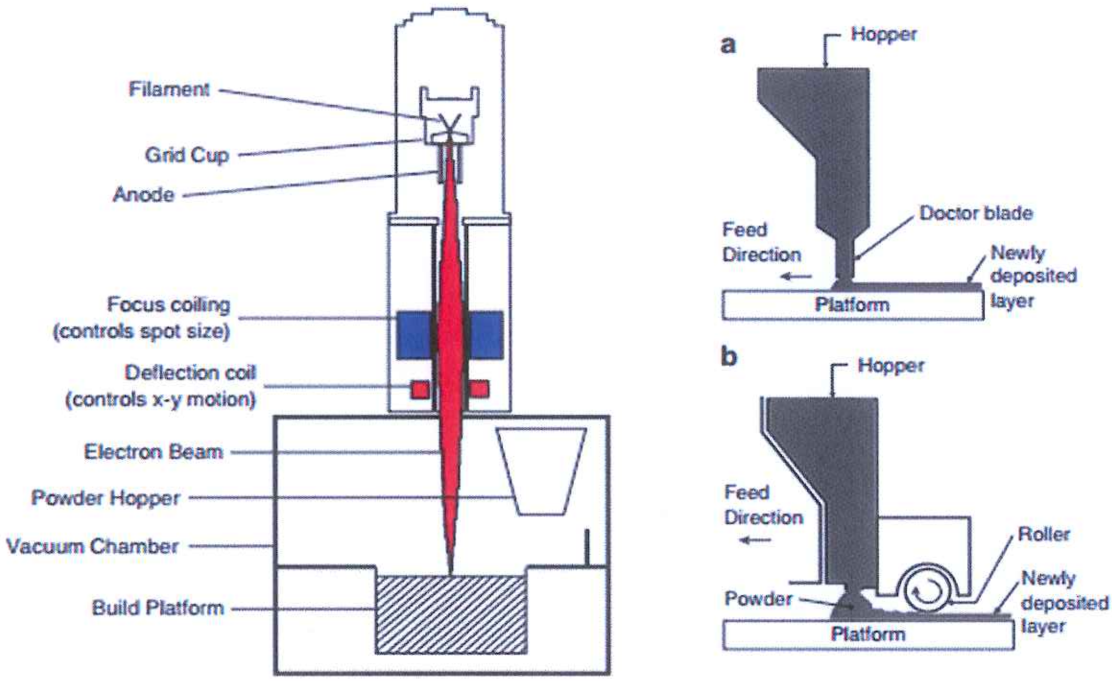


Figure [4.3] A schematic of an EBM printer (left) and a typical powder hopper delivery system (left)

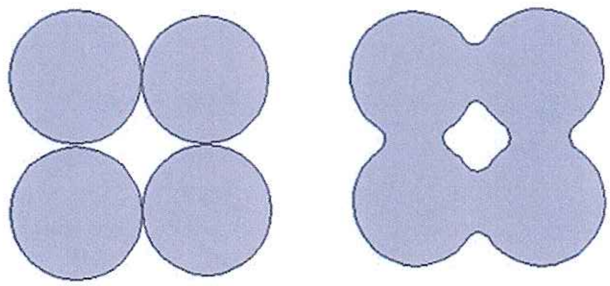
The electron beam scans the surface of the powder bed, targeting the specified cross section of the object. The beam provides the material with the extra energy required for melting. At the targeted area, the small powdered particles begin to fuse, or sinter. The size of the molten region depends on the electron beam energy, beam spot size, environment temperature and the conductivity of the powder. Both melt pool size and melt pool depth are a function of absorbed energy density. A simplified energy density equation can be used to model how energy density $E_A$varies with scan speed U, electron beam power P and scan spacing between parallel scans SP

$$E_A = P/(UxSP) \qquad (8)$$

Note that this approximation does not include powder absorptivity, heat of fusion, beam spot size, or other important characteristics.

The beam spot size is typically $\sim 0.2mm - 1.0mm$ (9) and molten pools are typically $0.25 - 1\ mm$ in diameter and $0.1 - 0.5\ mm$ in depth (7 p. 240)

A representation of sintering can be seen pictured right. As the powder is heated the particles agglomerate and begin to neck (join). The porosity of the sintered powder relates to the size of the 'hole' in the middle of the 4 particles. The longer the powder is left at elevated temperature, the smaller this 'hole' becomes. When this hole disappears, the powder is said to have zero porosity.



Representation of the initially unsintered powder particles. Represention of Sintered Powder Particles

Figure [4.4] A diagrammatic representation of particle sintering

Once a layer has been completed, the build platform drops vertically down and the hopper distributes a new layer directly on top the last completed layer. The process is repeated until all layers have been completed.

EBM requires a conductive build material; hence it is usually associated with metallic builds. Powdered titanium is a common build material, although in reality this is usually a complex mixture of titanium and many other metals in small dose. Powder size is usually between $0.045 - 0.1\ mm$.

Care must be taken to ensure that 'part growth' is minimised. This is where the powder surrounding the targeted molten area heats up via conduction, and can itself melt. Part growth is hard to control once initiated and can affect final product shape. Spontaneous sintering of particles in the powder bed also needs preventing. This happens when the particles randomly sinter with one another due to the elevated ambient temperature.

Sintering of unused powder is undesirable as it limits the number of times powder, unused in the powder bed, can be recycled. The mechanical properties of the final product depend largely on the quality of the print. Beams scanned too quickly can result in a highly porous final product (can exceed 50%) (7 p. 119). Thus, some part growth residual powder sintering is often accepted as a compromise for higher quality final product.

Another drawback of the rapid heating provided by the electron beam is warping. The melting point of titanium is $\sim 1600°C$. The rapid temperature gradient and localised nature of the heating can create stresses within the product due to thermal expansion. This is minimised by thermostatically controlling the environment temperature so that the material surrounding the target area is at a similar temperature. When using metallic powders, which are especially susceptible to warping, supporting rods may have to be incorporated into the print to fix parts of the print in place throughout the process.

The build tank must be left to cool under controlled conditions after the process has finished. For example, with titanium builds temperatures must be cooled to below $\sim 150°C$ before the build tank is removed from vacuum to prevent any oxidisation. This can take up to 12 hours and can severely limit the productivity of a machine.

Once the build tank is removed it can be transferred to powder recovery system. A high pressure jet is used to blow the un-sintered powder off the sintered build. This is performed in a sealed unit, which collects the residual powder for further processing. Up to 95% of the un-sintered powder can be recovered (9). After recovery, the powder can be passed through a mechanical sieve to reduce particle size back to an appropriate level for re-printing.

The final product may need to be moved on to finishing processes to further improve quality. These include

- Furnace Processing – The object is heated for a prolonged period at a temperature at which the particles start to neck (analogous to the unwanted powder sintering of unused powder described earlier) with each other. This dramatically reduces porosity. However it does cause a degree of shrinkage.
- Infiltration – A compound with a lower melting point is used as a filler. This method can produce more desirable alloy/compound properties. There is also no shrinkage.
- Surface Finish – The product is buffed and cleaned in the same way that an object obtained through subtractive manufacturing would. This would also include the removal of any support rods (as described earlier).

Example: The Arcam A2 & Arcam S12

At the Mercury Centre I was able to observe two EBM processors at work. They were both produced by the technology company ARCAM and both based on the principles described above. The S12 was the original model and the A2 released later. The primary improvements were a bigger build tank, a greater accuracy, a greater scan speed and thus greater build speed.

	Arcam S12	Arcam A2
Build Tank	$[250 \times 250 \times 200]\ mm$	$[350 \times 350 \times 200]\ mm$
Surface Finish	$\pm 0.4\ mm$	$\pm\ 0.2\ mm$
Scan Speed	$> 1000\ ms^{-1}$	$8000\ ms^{-1}$
Build Speed	$60\ cm^3\ hr^{-1}$	$80\ cm^3\ hr^{-1}$

(9)

The Arcam's were operating with titanium alloy powder. I also had the opportunity to see the processing of the powder using the auxiliary powder recovery system and mechanical sieve.

Both the S12 and the A2 are very similar in design. Pictured below, the S12 (left) and A2 (right) both contain an integrated computer operating system, complete with integrated interface. The small circular hole seen on both machines is a window into the build chamber, which has an x-ray shield for protection during use, as found on the EBW processor.

Right: This is the opened build chamber of the Arcam A2 immediately after a finished build. The smoothed powder bed can be seen in the centre of the chamber, with the build platform directly under it.

As the layers are completed, the build platform falls. The finished product is enclosed in the white un-sintered powder cube below the powder bed.

At the bottom of the picture are the powder trays which have been removed from the bottom corners of the build chamber.

Left: The powder cube above can be removed from the build chamber and placed into the powder recovery system. Here the final product can be removed from the un-sintered powder by a user operating a high pressure air hose. The removed powder is sucked up and sent to a mechanical sieve. This grinds the powder back down to a grain size appropriate for reuse.

5. Advantages/Disadvantages

5.1 Post-Production Assembly

Traditionally the production of any mechanised object requires construction of multiple parts followed by post-production assembly. For example

- Car Gearbox – assembly of gears onto a gear train
- Ball Bearing Hub – assembly of ball bearings into roll cage, which itself fits into two concentric rings (an inner and outer race)

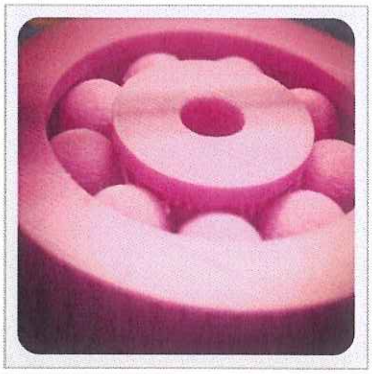


Figure [5.1] A polymer Ball-Bearing, created entirely in one print using a RepRap Huxley Machine

Through ALM the need for post-production assembly can be minimised. Mechanised designs can be created in entirety using CAD and then transferred directly to printing. The printer can print the whole object as one part. The only post-production required is the removal of un-sintered powder in the recovery system. The object should work immediately (after any required lubrication). At the European Aeronautic Defence and Space Company (EADS) at Filton Aerospace they have even managed to produce an entire working bicycle in just one print.

However, it is worth noting that while post production is minimised, it is rarely completely eliminated

When printing by EBM, no surface treatment is required because the localised heating caused by the electron beam gives a precise finish ($\pm 0.13mm$ for the Arcam A2 (9)). Other forms of ALM, particularly those that give cruder surface finish such as the beam deposition printers, will require surface processing post printing. This can be carried out by traditional methods for example filing, buffering, polishing, etc. Even in EBM, post production may be required. For larger builds where support rods have to be incorporated, post-production will include their removal. Again, this is typically performed by traditional machining methods. Also, as mentioned, furnace processing/infiltration may be required after some ALM techniques. These would also be included under the bracket of post-production.

The overall cost of production is largely dependent on the time it takes to make, and the additional cost of labour has to be factored in to products requiring assembly. Minimising the duration of the print is limited because fast prints often come at a compromise to the mechanical properties of the final product. Therefore minimising the amount of post-production is of great importance in improving the economic viability of ALM.

5.2 Complex Shapes

ALM allows the creation of complex geometrical shapes that would be impossible to create through traditional methods. Traditional production methods of creating complex/unique geometries require highly specialised tooling. This unique tooling often requires design and production itself, the cost of which must be factored into the cost of the final product. In the production of highly specialised components that are unlikely to be mass-produced, these tooling costs can greatly increase overheads. Since every print is created in the same way, independent of design shape/size, ALM prints mean that unique parts can be created without any need for unique tooling. This gives designers more freedom to trial new ideas without the financial constraints of traditional methods.

5.3 Size/Complexity Limitations

There is a limit to the minimum size/ complexity of mechanised parts produced by EBM. It comes from the properties of the build powder material. Highly complex geometries, for example internal cooling channels rely on the fact that all un-sintered powder can be blown out of the channels in the post processing stage. If the channels are two narrow, or take complex paths throughout the body of the object, it can be difficult to remove all residual powder. It is not simply a case of making the powder finer either. Ultra-fine powders often don't flow as well as well as courser powders (consider the flow of grains of sand compared to powdered flour). Research into improving the removal of residual powder would no doubt increase the versatility of ALM.

Figure [5.2] An example of Internal Cooling Channels, created using an Arcam EBM Machine

There is also a limit to the maximum build size available. The Arcam A2 works with a [350 x 350 x 200] mm build tank with a maximum build size of [200 x 200 x 350] mm. This is the largest EMB build size currently available. A number of problems are associated with increasing the size of the build tank

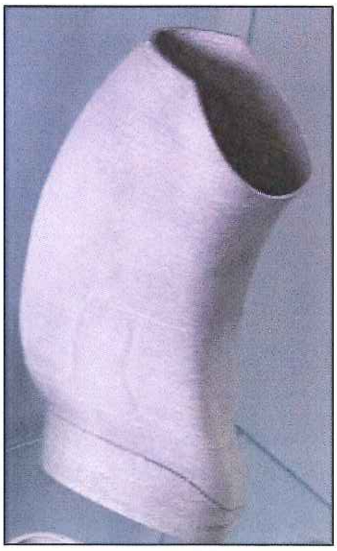
- Difficulty ensuring homogeneity of the build powder
- Difficulty maintaining a thermo-static temperature throughout the build powder.
- Increased duration of the build results in a greater level of unwanted sintering within the unused powder. This reduces the recyclability of the unused powder

- Limitations to the maximum angle of deflection of the electron beam. Thus for larger builds, the electron gun would have to be housed further from the build platform. Beam spot size is proportional to the distance from the gun to build platform thus a small spot size will be compromised. This would result in an increased melt pool size and increase the build tolerances.

Much larger build sizes are available from the beam deposition process. However large builds carry the added complications associated with handling large/heavy products. Removal from the printing chamber and post processing of large prints might require machinery. Also, the larger the build chamber, the harder it would be to maintain a vacuum, vital for electron beam production.

5.4 Tailoring of Material Properties

The strength-to-weight ratio of objects can be improved using ALM. This is particularly important in the engineering industry. Bulk solid objects can be tested under stress. Computer analysis enables 3D strain mapping of the results, which indicates which areas of the bulk solid are subject to the most stress. Using CAD the object can be hollowed and a load bearing skeleton can be designed to replace the original bulk. The improved object can then be printed. Externally the object would look identical to the original. It would also perform similarly under stress but with a dramatic decrease in weight. This process is again limited by the fact that residual powder could remain trapped within the structure, especially if the internal skeleton is very complex. Pictured below left is the vertical axis wind turbine prototype printed at the Mercury Centre. Part of the 'skin' has been left out to reveal the internal skeleton structure. Alternatively, sections of the bulk that don't bare any stress can be identified and shaved off, giving a more organic looking final product. An example of this can be seen on the component of an F1 car is pictured below right.



It's not only mechanical properties of materials that can be improved. The slow-controlled nature of ALM, combined with high quality build powders, produces products with an incredibly pure atomic structure. The lack of impurity ions leaves the build material well-bonded with much improved thermal properties. These improved thermal properties would be important anywhere the component is operated under stress at high temperature (for example the blades of a jet turbine). Electrical conductivity can also be tailored during the build, with the controlled addition of doped ions mixed into the un-sintered powder. Electrical conductivity would be an important consideration when printing electrical circuits.

5.5 Multi-Material Prints

The big drawback in EBM currently, is the inability to incorporate different materials into the same print. Multiple hopper systems have been prototyped, which enable different materials layer-by-layer. However they have had little success and there has been no progress on the industrial scale.

Multi-material printers with the ability to process polymers are just starting to be realised. They will be documented later.

5.6 Speed

ALM is relatively slow with builds taking hours or even days. This is very slow relative to tradition techniques used in mass production which can churn out hundreds of products every minute.

The only conceivable way of improving build speed is through faster heating by the electron beam. Commercial 3D printers currently exhibit multiple melt pool technology. This is where more than one electron beam scans the build surface at the same time. The Arcam A2 EBM can effectively print using 300 beam spots through efficient splitting of a single laser beam. This greatly improves the speed of prints, but even the A2 only processes with a build speed of $50cm^3\ hr^{-1}$

The limitations associated with faster scans speeds are poor product finish and much weaker bulk properties.

5.7 Economic Benefits

Currently electron beam ALM is only found in research laboratories such as the Mercury Centre (Sheffield) and in specialised industries such as aerospace, motorsport and bio-medical engineering. The Aerospace and Medical sectors are the only industries currently mass-producing components. These highly lucrative industries generate much of the funding that goes into R&D. It is likely that as developments in electron beam ALM continue, the cost of the technology will decrease. This, coupled with an increase in the diversity of printing units available will increase the accessibility to others wishing to utilise ALM technology. Industrial manufacturing market growth rates from 2011 into 2012 were greater than 100% and this year the increase continues to rise (10). But it's not just big businesses that should have an interest in ALM.

Small Businesses

The increased design freedom given by ALM without the traditionally large associated costs would be instantly noticeable to smaller companies with tighter budgets. Product development will be quicker and more efficient, and modifications to existing products could be made with relatively no extra cost. Companies wishing to experiment with their products, seeking increased functional performance will be able to do so.

Consumers

Others wishing to utilise ALM technology might be the consumers themselves. The RepRap printers described previously are available to the mass market at low cost and the number of units sold is increasing every year. It is estimated that 2500 machines have been purchased worldwide (11). These machines are only capable of polymer prints, but the consumer benefits seen by simple RepRap machines indicates the potential benefits that could one day be seen by more complex printer designs.

Consumer printing could change the face of design and production. With access to CAD design software and a 3D printer, the consumer becomes both the designer and the producer. An online marketplace currently exists where RepRap enthusiasts can download designs to print themselves, or upload their own designs for others to print.

Much of the cost associated with the design of a new product goes into market research. With consumer created products there is no need to make large investments in market research. This effect will be felt strongly in niche areas such as model kits for example Airfix, Train Sets, etc. Enthusiasts will be able to share designs and prints with no need for regulation or large scale manufacturers. Pirated designs (copies of patented designs/ copyrighted products) may one day become as big a problem to the manufacturing industry as download piracy is to the music industry.

The reduced dependence on large scale manufacturers will come with a decrease in the number and size of existing production facilities such as factories. The access to local printers would also cut out the need for a postal/distribution service, and consumers would face no delivery charges.

The specialised equipment used in EBM printing, and high start-up costs, mean it is unlikely that EBM will be ever be as widely distributed as the RepRap machines are. Indeed it may never be available domestically. The size alone of EBM machines would make mass distribution difficult. However, what could happen is the setup of public 'libraries' which give regional access to an EBM machine. Here, consumers could get their desired designs printed for a charge. An online market place could exist similar to that already seen in the RepRap printing community. It could be argued that even if mass distribution is realised, EBM tends to only be used to machine expensive high calibre parts, out of synch with the average consumer's needs.

6. Applications of 3D Printing

6.1 Prototyping

Due to its simplicity and ease of use, ALM was originally used to create prototype products. In this method Prototypes can be made quickly, accurately and relatively cheaply compared to the tooling used in traditional methods. These prototypes can then be subject to testing. Depending of the results of the testing, the designs can be easily modified using the CAD software and improved prints can be made. This process of design testing can be repeated until the desired outcome is achieved. In this way, part of the design process which would have originally taken months, can be completed in weeks or even days.

At the Mercury Centre, design testing was being carried out by the civil engineering department. Students were identifying the most suitable arrangement of cross beams in a load bearing structure in order to give it the greatest strength. A scaled down build of the structure was printed and subject to load testing. The results were recorded and the cross beam positions were altered using the CAD software. Many prints were tested and the best result were identified and moved to the production stage.

It's not just mechanical strength that can be tested, other properties such as aerodynamics can be analysed by testing the print in a wind tunnel.

As ALM is so suited to this method of prototype testing it is likely that it will take over as the number one method of doing so.

6.2 Medical Implants

ALM technology has taken over as the primary method of production for many medical implants. New bone replacements (see right) dentures, and even skin grafts are all being produced using 3D printers.

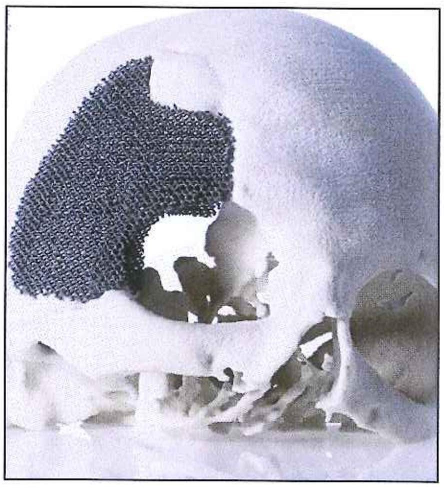


Figure [6.1] A porous bone replacement created using EBM has been fitted to this skull.

ALM is suited to the production of such items because each design can be custom made to the exact specifications of each individual patient. The risks associated with surgery are directly proportional to the time spent in theatre. Tailored implants will be much easier to fit than generic models, reducing the duration of operations and saving lives.

Through ALM the main body of the implant can be easily coated with a thin bio-compatible film preventing rejection from the host. Also, porous prints can be used which enable tissue growth within the implant, aiding bio-compatibility further.

Rarer applications of ALM in the medical sector see surgeons reconstructing exact replicas of patient's organs constructed from relevant CT (computerised tomography) scans. This enables them to practice complex operations on the dummy organs, giving them more confidence when carrying out the real thing. This technique is still in a stage of infancy, but as ALM techniques improve, the scope of this application will increase.

6.3 Aerospace/Motorsport

As mentioned, ALM enables the production of lighter weight, more organic parts. This is of great benefit to both the aerospace and motorsport industries.

In the aerospace industry, where materials are often very expensive, they have coined a term with specific reference to the importance of efficiency of manufacture - the buy-to-fly ratio. The buy-to-fly ratio is the weight ratio between the raw material used for a component and the weight of the component itself. This is typically around 15-20 for many components, but through ALM this can be reduced to very close to 1 (9).

Functional aspects can be improved such as aerodynamic performance. The Bloodhound Supersonic Car, which attempts to break the 1000mph land speed record later this year, contains many parts produced by ALM. The Nose Cone was produced by the Mercury Centre using EBM technology, and can be seen right.

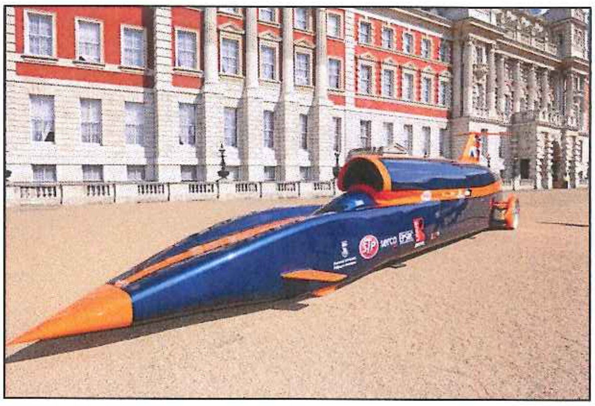


Figure [6.2] Bloodhound SSC: The orange nose cone was created using EBM at the Mercury Centre

Thermal properties of parts can also be improved due to the greater atomic purity of ALM products. For example the heat resistance of a material can be improved, an important factor affecting the performance of the material as a turbine blades/ brake pad.

ALM is used extensively throughout F1 motorsport. The rapid prototyping nature of ALM lends itself to a process known as aero development - repeated testing of new body kit designs in wind tunnels. The use of ALM has now expanded to include the direct manufacture of actual components for racing such as a gearbox.

7. New Printer Designs

New methods of powder bed based printers are being developed.

7.1 Line-wise/Layer-wise ALM

Two examples of new print technologies are known as Line-wise and Layer-wise processes. In these processes rather than scanning a beam across the powder bed, building the object a point at a time, whole layer sections are created at a time. Two current methods for doing this are

- High Speed Sintering (HSS): In this technique, invented at Loughborough University, a dye is printed on only the areas within the desired object cross section. This dye is highly conductive and promotes heat transfer between a heater and the powder. The entire powder bed can then be exposed to an infra-red heater, held at such a temperature that only the dyed powder is sintered. An undesirable outcome of this process is the presence of dye in the final product, which will limit the colour

- Selective Inhibition Sintering (SIS): A dye is printed on the powder bed covering all areas outside the desired object cross section. This dye has excellent heat resistant properties. Similarly, an infra-red heater can then be applied to the entire powder bed, but this time only the un-dyed powder is sintered. This has the advantage that the final product contains none of the dye. However, it does means that the unused powder is contaminated with the dye and will not be recyclable.

7.2 Poly-Jet ALM

Multi-material printing technology is being developed by Stratasys, who specialise in the development and production of Poly-Jet ALM.

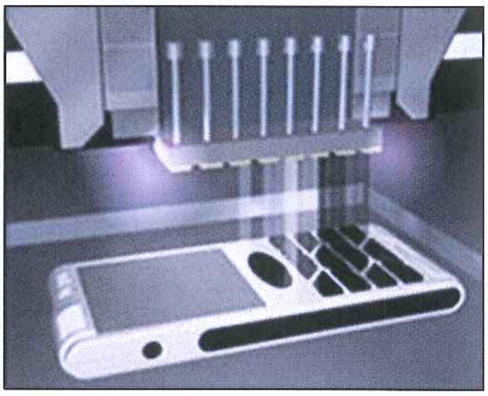


Figure [7.1] A computer graphic of a Stratasys object1000 printing a multi-material prints

As the name suggests, Poly-Jet ALM works in a similar fashion to Ink-Jet 2 dimensional printing. It does not involve the use of electron beams, but for generality the basic process will be explained. Microscopic droplets of liquid photopolymer are jetted from a delivery system onto the build tray one layer at a time. With each completed layer, the build is exposed to UV light which cures the polymer.

Their 'Objet1000' offers a choice of over 100 materials ranging from rigid to rubber-like with a vast variety of material properties. This is the only machine currently available capable of multi-material prints. 2 materials can be 'loaded' into the two delivery systems at any one time, and up to 14 materials can be incorporated into any one design. Composite materials can also be printed, by combining the two delivery systems in specific concentrations providing desired material properties.

8. Directions for R&D

To summarise the advantages/disadvantages described in chapter 5.

Advantages	Disadvantages
Ideal for prototyping complex products in smaller batch size	**Not suited to mass production of simple items**
Post Production is minimised.	Post-Production not eliminated.
Production of complex geometries.	Single material prints.
High material utilisation.	Still relatively expensive.
Custom Material Properties.	Limited choice of materials.
Allows design modification with minimal time and cost.	Slow Build Speed.
Production at point of demand.	
Consumer created products.	

These disadvantages indicate areas for research and development if ALM is to take off. Key areas for research and development, are given below.

8.1 Development of Multi-Material Prints

Multi-material printers with the ability to process polymers are just starting to be realised. No multi-material printers exist that can process metallic materials. Indeed none of the new designs described involve electron beams at all.

It is unlikely that EBM printer designs will ever be able to produce multi-material prints due to the nature of the powder delivery systems. It is not feasible to create a multi-material product by varying the material layer-by-layer without any cross layer bonding. For example, it would be impossible to create an object consisting of an external shell of material x, with internal components of material y

Multi-material printing could be achievable through the beam deposition processes with the use of multiple feedstock nozzles. Each nozzle could feed a different material, with all feeds deposited using a single electron gun. The nozzles would have to be mobile, and be capable of positioning themselves into the right position for electron beam heating. Alternatively, the nozzles could be fixed, as in traditional electron beam welding and the baseplate could move under each appropriate nozzle. The disadvantage of multiple fixed nozzles is that it would involve multiple electron beams

(one for each nozzle), since moving a single beam would be difficult. It would therefore require more power.

I believe that if 3D printing is to continue to develop, the inability to print multi-metallic products provides a huge limiting factor on the possibilities of ALM. Many polymer materials such as graphite can exhibit superior mechanical properties (such as strength to weight) to metals. These substitutes are adequate for a number of structural applications. However, once the ability to print using different metals is realised the number of possible applications of 3D printing will dramatically increase.

For example, if printers could one day process metallic and polymer materials simultaneously whole electronic circuits could be printed. No circuit assembly would be required, and editing could be performed with the click of a mouse. Wires could be printed with insulating rubber enclosing them. Development in the precision of prints (i.e. decreasing tolerances) will enable the production of smaller and smaller electronic circuitry. Faults due to human error associated with traditional assembly would be eliminated.

At the moment, there is no conceivable method of multi-metallic printing. The difficulties lie in creating a definite metal-metal interface at high temperatures, where both metals are above their melting point. In traditional processes, different metals are simply fixed together using nuts/bolts/screws. In order to bond two metals through ALM, the beam has to traverse the interface. Half of the beam will melt metal A, and the other half, metal B. The delocalised nature of electrons and ions within the metal causes metals to bleed into each other rather than forming a clean interface. This leaves alloyed sections within the build, with material properties that are difficult to control.

This intrinsic problem will likely make creating multi-metallic prints though EBM/EBW impossible.

8.2 Software Development

A problem expressed by James Hunt, of the Mercury Research centre concerned the sophistication of the CAD software currently available. Since design takes up a large portion of the production time, improvements in the CAD software are as relevant to the development of ALM technology as improvements in the printers themselves.

The process of incorporating support rods into a product is currently a manual process. The positioning of individual support rods requires careful consideration by the designer. Often, the results of independent stress/thermal tests must be referenced. If the required information is not available, original tailor made testing must be carried out.

If software could be developed to automate support rod positioning the design time could be reduced. If a database of stress test results was created, software could be designed to reference relevant results when making the decision of where to position support rods. Alternatively, the software could make the decision through computer simulation of stress/heat testing.

Another problem associated with current software is poor conversion of scanned in objects to STL (Stereo Lithography) files, which are recognisable to the printer. Parts of the scan are often lost in the conversion, and require filling in manually afterwards. Improvements in conversion software will help eliminate this.

New digital interfaces that enable non-experts to design products are needed for the development of ALM in the consumer market. These should be easy to use and automate many of the functions available on expert CAD software.

8.3 Diversification of Machines

The accessibility of ALM relies on the diversification of machine sizes, speeds and accuracies. In order to get as many people using it as possible, the number of machine models should increase, with each model specialising in certain materials/sizes. For example, the highly technical equipment associated with electron beam printing mean it is unlikely that this will every find its way into the home. Therefore, this technology may remain in industry, where bigger printers will be needed to supply the demand for large components. However, as it is the only current way of processing metallic prints, libraries could be set up where consumers could carry out any metallic printing required.

Polymer printers are already much more diverse than their metallic counterparts. Large polymer prints are currently available such as the Objet1000 described earlier which is capable of $[1000 \text{ x } 800 \text{ x } 500]\ mm$ builds. The build size is increasing every year. Conversely, many domestic printers are already available to hobbyists. Some believe (12) that progress of 3D printing lies with children; specifically, children using child-friendly printers to print their own toys. These toys could be designed by the children themselves, or by toy manufactures whose designs could be purchased online.

It is important that this diversification doesn't limit the versatility of what can be produced with each individual model; this is after all the driving force behind the development of ALM technology.

The limitation to the minimum size / maximum complexity caused by the inability to recover trapped un-sintered powder within the build also needs to be address. Perhaps the development of some

kind of solvent that only acted on the un-sintered powder could be developed. This would enable the un-sintered powder to be simply washed away.

8.4 Build Size

Filament bulbs used to produce electron beams have a lifespan of ~40hrs. If the capacity of build tanks is increased, longer builds may exceed this. In current systems removing the bulb during the process wouldn't be feasible as the system would have to be taken out of vacuum. Before this could happen the build would have to be control cooled to avoid any oxidation. New systems could be developed where the filament is housed in a load lock chamber. This would potentially enable the filament to be changed whilst maintaining the rest of the build at vacuum.

9. Conclusion

It is easy to suggest that ALM could cause a fundamental restructuring of the traditional production chain. True, it enables digital blueprints, created anywhere in the world, to be utilised for production anywhere in the world. It cuts out the middle man, removing the need for third party manufacturers. This is an exciting prospect, but having conducted this report, I believe the limited size capacity, small volume turn-out and slow build speed will mean that it won't replace tradition production methods for simple mass produced goods (eg. Cars, domestic appliances, furniture, etc.). I also don't envisage electron beam ALM being available domestically in the near future. If the cost of the technology substantially decreases, polymer ALM could potentially take off in new areas such as toy manufacture, but it is hard to envisage the initial costs of printer/materials ever balancing simply buying mass produced toys.

That said, what is certain is that ALM is ideally suited to creating complex components in small quantities. The increased design freedom will ensure that ALM will continue to flourish in aerospace, motorsport and medical sectors. Also due the simplicity and the removed need for specialised tooling ALM will continue to extend its use in prototyping, ultimately taking over as the number one method of doing so.

For the technology to continue to develop there is a need to

- Minimise post-processing
- Increase accessibility through a reduction in the cost of equipment/materials
- Increase accessibility through a diversification of machine sizes, speeds and accuracies
- Develop multi-material print technology (including multi-metallic prints)
- Improve associated software

During this project I have developed my knowledge of a new industry that is at the forefront of design and technology. Through comparison with traditional methods I have learned to appreciate the complex link between technology and economy.

If this project were to be carried forward, analysis into other methods of ALM could be carried out, in the same way that has been done here for Beam Deposition and Electron Beam Melting. A detailed analysis into the costs associated with the various ALM technologies could be carried out, and comparison made with the costs of tradition methods. This would enable more accurate predictions of the future prospects of each ALM technology.

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Please note that all other unreferenced photographs within this report were taken by me, whilst at the mercury centre.

Appendix A: Project Proposal

Name	Jerry Dillon
Student ID	200718862
Project Title	*The Industrial Application of Electron Beams with Specific Focus on 3D Printing*
Supervisor	Kai Hock

Main Objectives

To survey and analyse the literature currently available concerning Research and Development (R&D) of electron beam use in general, and in 3D printing in particular. Through summarising this information potential future directions for R&D will be proposed.

Supervisor Meetings will take place each week (Thursday 1200) to discus progress.

All raw data and day-to-day work will be recorded in the Project Diary (signed off by supervisor) which will be handed in as part of the final report.

Timeline

Week 1	Preliminary research into electron beam technology. Consider report structure. Record any key sources (Literature, Journals and Internet).
Week 2	Continue with preliminary research. Create and hand in ***Project Proposal*** complete with Risk Assessment.
Week 3	Review physics of electron beam technology and become comfortable with equations involved.
Week 4	Review application of electron beam use in general.
Week 5	Review application of electron beam specifically in 3D Printing.
Week 6	Review 3D printing machines currently available. How they work, how they differ from each other, etc.
Week 7	Analyse the commercial impact of R&D of 3D printing. Ex. How could it change business and manufacturing?
Week 8	Prepare for ***Oral Presentation***, including creating PowerPoint presentation.
Easter Holiday (3 Weeks)	*Potentially organise a trip to Filton Airspace to see first-hand a working 3D printer in use.*
Week 9	Research potential future directions of R&D in 3D printing.
Week 10	Collate all information obtained and start to construct final report.
Week 11	Continue with construction of final report and complete source referencing.
Week 12	***Project Report*** hand-in (Fri . 10th May).

Appendix B: Personal Reflection

I have always been fascinated by ALM technology, and it was for this reason that I decided to make it the focus of my project. I first encountered ALM while working in the summer for eMaker. This small business assembled simple 3D polymer printers (Model: RepRapPro Huxley) for packaging and sale. I was originally impressed with the machines ability to print its own replacement parts, and replicate itself. Working here sparked an interest in the technology and I wished to investigate other forms of ALM further.

At the start of my project I planned to visit EADS (as mentioned in my project proposal) and observe electron beam printing in person. I contacted them but unfortunately, due to health and safety requirements, they would not permit me access to their printers. I was pleased then, when the Mercury Research Centre, another facility I had been in contact with, welcomed me to their site in Sheffield for a look at EBW and EBM printing.

Here I met James Hunt, a manufacturing officer at the Mercury Centre. He allowed me access to all their ALM machines and I was able to see them working. I was able to gain further insight into the technology, and had a chance to hear the opinions of an expert in the field. I developed my understanding of ALM, and what its current limitations are going forward. He was very helpful and spent a lot of time with me explaining the details of ALM manufacture.

I am pleased I took the project as I feel I have developed my knowledge of 3D printing and gained an understanding of its future prospects. I hope this has come across in the report. Personally, I have learned to appreciate the importance of individual focus and self-motivation, through carrying out a report with little external help. I have also gained a reinforced understanding of the importance of time management. I feel I kept to my project proposal well and carried out all weekly plans. Through contact with a number of research centres, enquiring about access, I feel I have developed my communication skills.

Through the oral presentation I feel I have developed my perceptions of what it means to give a good talk. I am told I spoke clearly and coherently, which I was pleased about as I was nervous beforehand having never given a talk of that duration before! I was also told I employed use of good PowerPoint slides to help get my points across. Some negative feedback I received was that I was not always engaged during the talk. In certain sections I probably relied too much on what I had prepared rather than talking about what I already knew. This is something I recognise and I will be keen to put right going forward.

Throughout my project, I found that the lack any real experimental work, made it difficult for me to convey my own contributions. For example, if I had my own set of experimental data I could have carried out a lot of physical analysis. I know that the lack of experimental work was made clear to me from the outset, as specified in the project outline given to me at the beginning of the course. However, I did not realise/appreciate the extra difficulties associated with constructing a 'literary analysis', until I was deep into the project. I may have dedicated too much of the report to the functioning of ALM machines, rather than the R&D directions, but I felt that without an understanding of how the processes worked, suggestions for R&D would be baseless. The lack of experimental results has also left my log book thinner than those with raw data. Much of the report was typed directly into word, with no need to use the log book. I did however find it useful for recording my ideas whilst at the Mercury centre.

If I were to extend the project, I would try to go about producing some real prints myself. Through actually using the machines to produce models, I feel I would gain a deeper understanding of the pros/cons of current ALM technology. Unfortunately at Liverpool we do not currently possess any electron beam printers, but I could seek access to the Mercury Centre or similar research facility, provided I contact them.